Lean Premixed Turbulent Methane Combustion with Hydrogen Additions: Burning Velocities and Emissions Measurements

Y. C. Chen and S. S. Shy
Department of Mechanical Engineering, National Central University, Jhongli 32054, Taiwan

Corresponding author, S. Shy: sshy@cc.ncu.edu.tw

Introduction

This paper investigates experimentally lean premixed methane-air turbulent combustion with various hydrogen additions. Focuses are placed on measurements of turbulent burning velocities and variations of NO_x and CO emissions for these methane/hydrogen/air flames.

It is known that the study of lean premixed turbulent combustion is important to spark ignition engines (Heywood 1988; Bracco 1990) and gas turbines (Correa 1990) because of its potential for reduced NO_x emissions. When applying this lean burn technology, there are two major problems: (1) a substantial decrease of burning velocities S_L and (2) a large increase in misfires. To lessen these two problems, several attempts have been made, such as for instance, by Iguchi (1991), Akishino (1992), Nakanishi (1992), among others, using either higher ignition energy or stratified combustion. Though these attempts can certainly improve lean premixed combustion performance to some extent, to burn leaner mixtures at even higher burning velocities requires other methods. A small amount of hydrogen, as an additive, was applied by Kido et al. (1994). Since H_2 has a very low lean flammability limit with high burning velocities, the aforementioned two problems may be significantly improved.

A central issue in the field of premixed turbulent combustion is to determine the enhancement effects of turbulent intensities u' to turbulent burning velocities S_T that may influence all of important properties of premixed turbulent flames. Recently, a new methodology for accurately measuring turbulent burning velocities was proposed by Shy et al. (2000) using a large cruciform fan-stirred burner together with a pair of ion-probe sensors. In this study, a series of turbulent combustion experiments using lean methane/air mixtures with various hydrogen additions over a wide range of u'/ S_L in the cruciform burner ise conducted to measure the corresponding laminar and turbulent burning velocities using ion-probe sensors. In addition, measurements of pressure rise during turbulent combustion and NO_x and CO emissions are also carried out to investigate the effect of hydrogen addition and combustion characteristics of lean methane/hydrogen/air flames.

Experimental

Figure 1 shows schematically the cruciform burner that includes a long vertical cylindrical vessel and a large horizontal cylindrical vessel. A downward-propagating premixed flame with large surface area of about 10 cm in diameter can be generated by ignition from the top of the burner. The horizontal vessel was equipped with a pair of counter-rotating fans and perforated plates at the two ends to generate a region of intense near-isotropic turbulence for flame-turbulence interactions without the influence by ignition and unwanted turbulence from walls. This novel experimental design allows direct imaging and velocity measurements of the two-way interaction between premixed flames and homogeneous isotropic turbulence. Consequently, high-speed laser tomography, ion-probe sensors, particle imaging velocimetry measurements, among other means in the cruciform apparatus, amenable for qualitative understanding and quantitative analysis of various aspects of turbulent flame propagation, stretching, and global quenching, can be applied (Shy et al. 2000; Chang et al. 2001; Shy et al. 2001; Yang & Shy 2001,2003). In and by itself, we believe that the experimental design is a useful contribution to the study of premixed turbulent combustion.

Before a run, lean methane and air with various hydrogen additions (10 %, 20 %, 30 %) are well mixed in the mixing chamber, in which the equivalence ratio ϕ is ranging from 0.6 to 1.0. After evacuated, these mixtures are injected into the cruciform burner, and a run begins by ignition from the top. Sequential images of both laminar and turbulent stoichiometry CH_4/air premixed flames propagating through the central interesting region are obtained by a high-speed camcorder (Fig. 1). After a run, burned gases are sampled to measure NO_x and CO concentrations using NDIR (Non-dispersive infrared). Figure 2 presents the cruciform burner with a pair of ion-probe sensors positioned at several different portions with respect to the central uniform region for S_T measurements. In addition, ten pressure released valves are distributed to both the vertical and horizontal vessels for modulating the pressure rise in the chamber during turbulent combustion.

Results

Results reveal that a small hydrogen addition not only can slightly expand lean flammability limit of CH_4/air mixtures, but also can increase significantly values of S_T. At fixed values of u'/S_L and ϕ (= 0.6, 0.7 or 0.8), values of S_T increase with the amount of hydrogen addition. However, turbulence cannot increase values of S_T continuously, and the slope of S_T/S_L *vs*. u'/S_L is found to bend towards the horizontal when values of u'/S_L are greater than about 4. This is the so-called bending effect, as also observed in burning CH_4/air mixtures with hydrogen addition. All the present data can be correlated with an empirical relation with the form of $(S_T - S_L)/u' = C_1 Da^{C_2}$, where C_1 and C_2 are experimental constant and *Da* is the Damköhler number, as shown on Fig. 3. This empirical correlation is first proposed by Shy et al. (2000) using the same methodology without hydrogen addition. Also plotted in Fig. 3 are previous data and the distributed reaction zone (DRZ) model from Shy *et al*. (2000) for comparison.

Emission concentrations of NO_x and/or CO are found to increase and/or decrease with the percentages of hydrogen addition, respectively. For examples, at u'/S_L = 2.0 and ϕ = 0.7, values of [NO_x] are respectively 98, 136, 158, and 188 ppm for 0 %, 10 %, 20 %, and 30 % hydrogen addition. This indicates that hydrogen combustion has to consider the problem of NO_x formation due to its high flame temperature. Values of [CO] vary from 40 ppm to 55 ppm for any values of u'/S_L ranging from 0 ~ 7 and at ϕ = 0.7. These experiments suggest that the hydrogen addition should not exceed 20% for lean premixed CH_4/air turbulent combustion and values of u'/S_L should be controlled within the range of 4 ~ 10. Thus, higher values of S_T/S_L ranging from 6.5 to 12 can be achieved with not too high [NO_x] emissions. These results are relevant to the combustion performance of natural gas fire power plants, and the use of hydrogen as an additive to natural gas should be an attractive solution both at present or in the near future for the energy problem.

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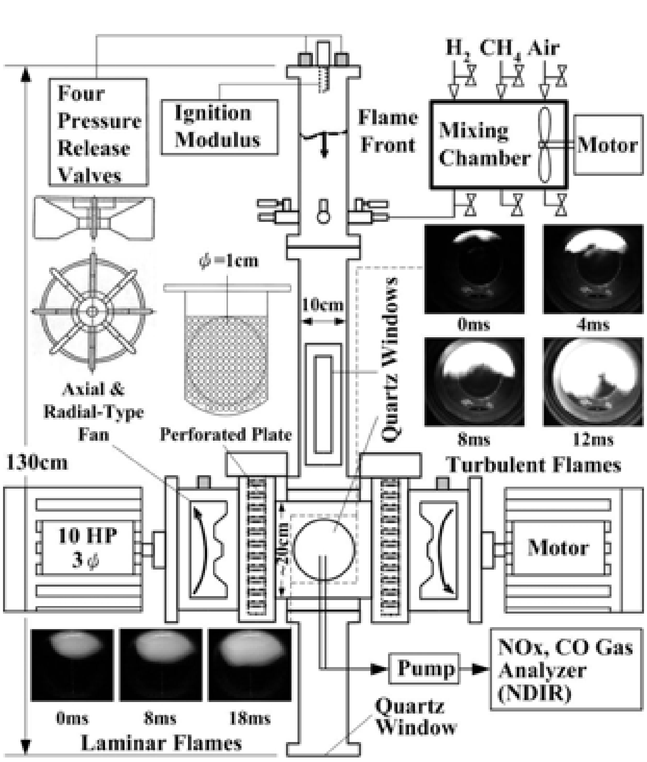

Fig. 1. The cruciform burner equipped with a pair of counter-rotating fans and perforated plates for creating intense isotropic turbulence in the core region between the two perforated plates. Sequential photographs of both laminar and turbulent stoichiometry CH_4/air premixed flames propagating through the central interesting region are obtained by a high-speed camcorder. After a run, burned gases are sampled to measure NO_x and CO concentrations using NDIR (Non-dispersive infrared).

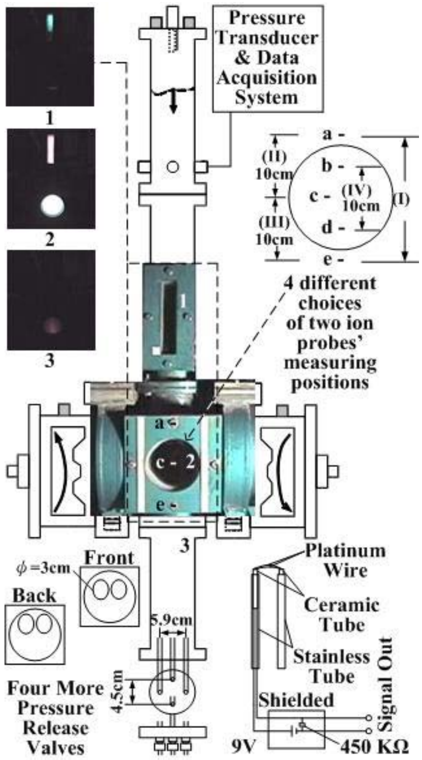

Fig. 2. Same as Fig. 1, but for the arrangements of pressure and turbulent flame speed measurements using the pressure transducer and a pair of ion-probe sensors, respectively. Three photographs show a typical evolution of turbulent premixed flame propagation.

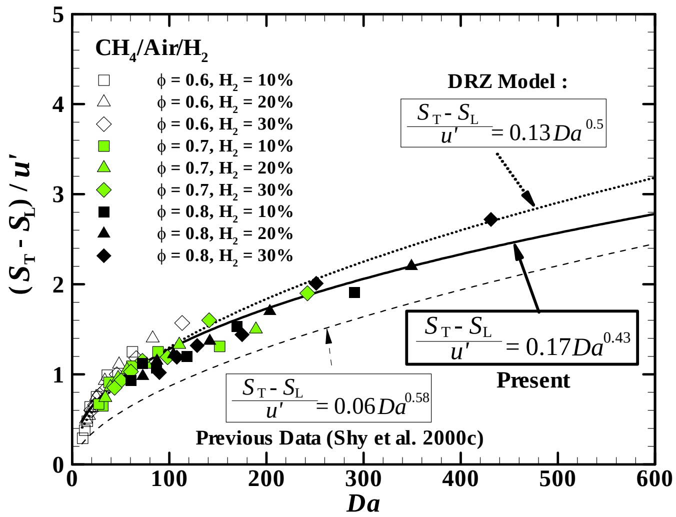

Fig. 3. A general plot of turbulent burning velocities, $(S_T\text{-}S_L)/u'$, as a function of the Damköhler number, Da. Also plotted are previous data from Shy et al. (2000) and the distributed reaction zone (DRZ) model for comparison.